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Study of the behaviour of adhesive joints of steel with CFRP for its application in bus structures

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ABSTRACT

In recent years, the use of adhesives in structural applications is growing, achieving a great current implementation in the industry, due to the benefits that this technology is capable of providing to complex-shaped structures, both in aerospace and automotive applications. Adhesive joints show many advantages in comparison with other traditional joints such as welded joints, because they offer a continuous joint with homogeneous stress distribution, they are able to joint dissimilar materials (such metals and composite materials) and they do not require large investments. Current bus steel structures present fatigue problems due to the rigidity of the commonly used welded joints. Crack problems due to fatigue are evident in the areas of the bus structure closest to the rear door, being the joint between the side vertical pillars and the waist rail the most critical. A finite element model (FEM) of a bus steel structure is developed, in order to obtain the forces that work on the reference node. From the obtained force values, the value and type of stress at the reference node are calculated. A new carbon fiber reinforced polymer (CFRP) node is developed, replacing the existing welded joint by steel-CFRP adhesive joint. The new node design allows to obtain mainly shear stress. Because of that, single lap joint specimens are developed to carry out the experimental procedure. This work is focused on the study of a structural adhesive for its application in this new type of joint taking also into consideration manufacturing criteria (mounting periods, costs, etc.). This new adhesive joint shows strength values an order of magnitude higher than the requests at the node, and higher than 30% of strain values, minimizing fatigue problems.

1. Introduction

Nowadays, there is a high demand for the design of lightweight energy efficient and safe structures for transport applications [1]. Vehicles for passenger transport in general, and coaches and buses in particular are under a great pressure, due to high competition, safety regulations and user preferences. The most common material employed is still the high strength steel, due to its good mechanical properties at a reasonable cost.

The bus body is typically made of beams with hollow rectangular cross sections joined together by means of welding technique. The main advantages of using welding technique are that the joining process is faster, robust and cheap, no filler material is required, and dimensional accuracy is better preserved during welding with local heating [2,3]. Nevertheless, the welding requires high temperatures which cause the formation of a brittle layer of intermetallic compound at the joint interface, making it difficult to obtain the desired joint strength [4]. It also presents premature fails due to corrosion, needing more frequent inspections. On the other hand, bus body is subjected to different dynamic loads which are transmitted from the pavement to the structure leading also to crack problems, principally in certain welded joints due to fatigue [5,6].

For these reasons, new concept designs, materials and assembly methods have to be developed and applied by bus and coaches manufacturers. Various research works have been carried out in

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order to study the introduction of different types of materials such as aluminium alloys [7–9] and composite [10,11], for bus and coach body manufacturing in order to optimize fuel consumption by reducing vehicle weight without compromising strength or safety. While fiber-reinforced composites have showed potential for automobile parts in the past several decades, the application has yet to be realized on a mass production scale due to several drawbacks including low production, automation rates, and significant costs [12,13].

Multi-materials design strategies are being adopted in many field of transportation not only in aeronautic and aerospace but also in automotive [14–16]. Structures built in that manner consist not only of regular steel parts, but contain also a mix of components made from various lightweight materials like aluminum alloys or composites, which allow for significant reduction in vehicle curb weight. However, due to the differences in mechanical characteristics that are especially evident in the case of laminates, the material substitution is not a straightforward task [17]. New assembly approaches with different materials are now possible thanks to the use of structural adhesives.

Structural adhesive joints are increasingly being used in the manufacturing of hybrid [15,18] and complex [19,20] structures for civil, automotive and aerospace applications. They present important advantages against other type of joints because it is a simple and flexible technique, it offers a continuous joint with a homogeneous stress distribution during loading, ability to join dissimilar materials (such as metals with composite materials), less corrosion problems (avoiding the formation of galvanic corrosion batteries) and does not require great inversions [21].

Recently, a number of works have been undertaken to study the behaviour of multi-material structural adhesives. In Ref. [22] the effect of the humidity-temperature cycling on mechanical performance of adhesively bonded joints is investigated. Agarwal et al. in Ref. [23] study the effects of thermo-mechanical loading in both wet and dry conditions on steel-CFRP (Carbon Fiber Reinforced Polymer) single lap-joints. In Ref. [24] the characteristics of the dissimilar adhesive joint of the mild steel and aluminium sheets as a function of the mechanical and chemical surface treatment of the substrates is investigated. Flow characteristics and wettability of the epoxy based nanocomposite adhesive containing different amount of TiO_2 with substrate are also taken into account. The effect of bond line thickness of the adhesive in lap joints of the differently treated faying surfaces of the dissimilar metals on lap shear strength of the joints is also studied.

In order to solve the issue of fatigue crack in welded joints of steel bus structures, a new concept of joint made with CFRP is proposed. The aim of this work is to redesign the joint achieving higher flexibility to redistribute the stress field towards adjacent joints. This joint is connected to the steel structure by means of an elastic-plastic adhesive bond. This work is focused on the study of a structural adhesive for its application in this new type of joint taking also into consideration manufacturing criteria (mounting periods, costs, etc.). To select the most critical joint of the bus, a 3D FEM model of a bus structure is developed. This model is also used to calculate the loads that the joint needs to resist. With the value of the estimated loads and the size of the overlap area, the adhesive is selected. The steel-CFRP adhesive joint has been characterized by means of stress-strain curves obtained from shear tests, showing the suitability of the proposal for the raised problem.

2. Bus FEM model

The experience has shown that the welded joints which more commonly suffer crack problems in bus structures are closer to the rear door and more specifically those welded joints which joint side vertical pillars with the waist rail. In order to confirm such assumption a finite element model (FEM) of a bus steel structure is used. The finite element analysis was carried out using ANSYS® code. This model allows to find the areas of the structure with higher stress problems, and gives the value of loads (in terms of forces and moments) needed to design an adhesive joint of steel with CFRP. Taking the results into account, authors decided to focus the study in the node depicted in Fig. 1 to provide an alternative solution.

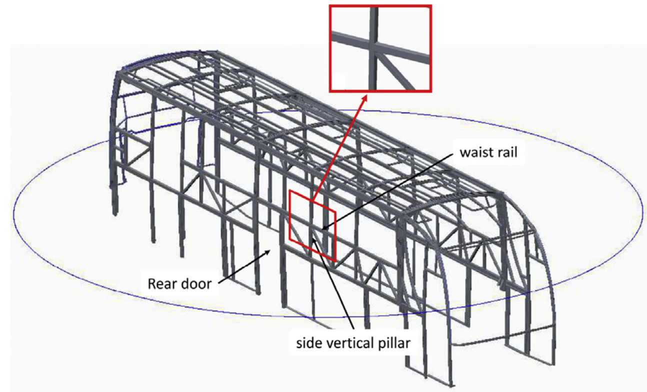

Fig. 1. Selected node.

The bus model has been built from the 3D geometry given by the manufacturer in STEP format. For this problem, a conventional "tridimensional solid elements" model is inappropriate, because of the high computational cost it can represent. A beams model could be adequate taking into account the geometric profile of the problem, but will not be good enough to calculate properly the stress distribution near to the joints and weldings, which are the most problematic areas in terms of stress values and fatigue resistance. A shell model has been selected, generating the mid-plane geometry model meshed with four nodes shell elements of 20 mm size.

The model has the following main characteristics:

- Number of nodes: 474.000
- Number of degrees of freedom per node: 6 (ux, uy, uz, rotx, roty, rotz)

The used material is structural steel whose properties are summarized in Table 1. A linear elastic isotropic model has been considered for the steel behaviour. The structure is expected to work under elastic conditions by the action of the considered loads. If the Yield Stress is found to be overcome in the model results, loads should be reconsidered, so linear elastic behaviour is an appropriate hypothesis since the loads do not take the material out of the linear elastic working range.

Solving the model for conventional load states that simulate conventional situations for a bus (braking, accelerating, curve passing, etc.) reasonable results have been found, with correct deformed shape and stress values always under 150 MPa.

Torsional loading cases have been studied because they generally result in large stress in the bus body. Displacements have been

Table 1
Properties of structural steel.

Property	Value
Density	7850 kg/m^3
Elastic modulus	210 GPa
Poisson's ratio	0.29
Yield strength	400 MPa

restricted adequately in the suspension connection points, depending on the load state solved in each case. For example, to simulate the torsion state, vertical displacement was restricted in each wheel connection point, with 0 value for three of them and a value of 5 cm for one of them (right front wheel). Longitudinal displacement, transversal displacement and vertical rotation was also zeroed in one point to avoid rigid body motion. Fig. 2 shows the stress distribution due to this torsional loading case. For the studied node, internal forces in each beam of the node are given in Table 2. Values are displayed respect to the reference system established by SAE J670e standard for motor vehicles (see Fig. 3).

3. Proposal of a new concept of node

The new node design to substitute the welded steel node must satisfy some requirements.

- The new design have to purchase strength enough to resist the previously calculated forces and moments.
- Dimensions must keep the geometry under the limits that the original structure sets.
- Stiffness must be adjusted to the optimized value that lets the designer to properly distribute the stress in the surroundings of the bus structure. To get this requirement it is important that the node design has some variable parameters capable to control the stiffness of the system by changing the design value.
- Another expected requirement is that the node design should facilitate the modular manufacturing of the bus structure. Expert welders are needed to build bus structures by the present technology. The new design should facilitate the building of the structure by assembling pre-manufactured parts without the needing of welding.

The geometric concept of the proposed design is shown in Fig. 4.

A composite material with epoxy polymer matrix and fiber reinforcement will be used because of the adequate balance of weight and strength that characterize such materials, being able to satisfy all the established requirements.

The adhesive must be found capable to resist the stresses generated by the node forces calculated from the bus FEM model. Axial forces act on the node, causing mainly shear stresses in the adhesive joint:

Table 2
Forces in each beam of the node due to the torsional loading case.

Beam	F_x [N]	F_y [N]	F_z [N]
6	−452.7	−79.0	−518.5
11	2361.2	−38.2	23.1
37	−4323.7	20.1	168.0
39	−306.5	100.5	−1999.5
44	2721.7	−3.5	2326.8

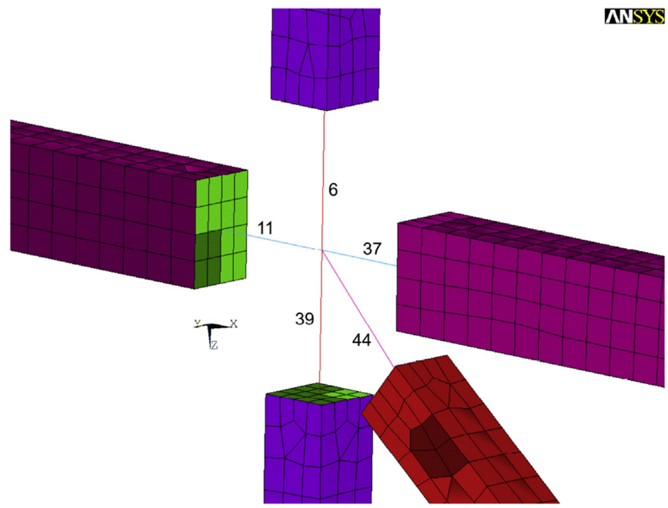

Fig. 3. Coordinate system in the bus FEM model.

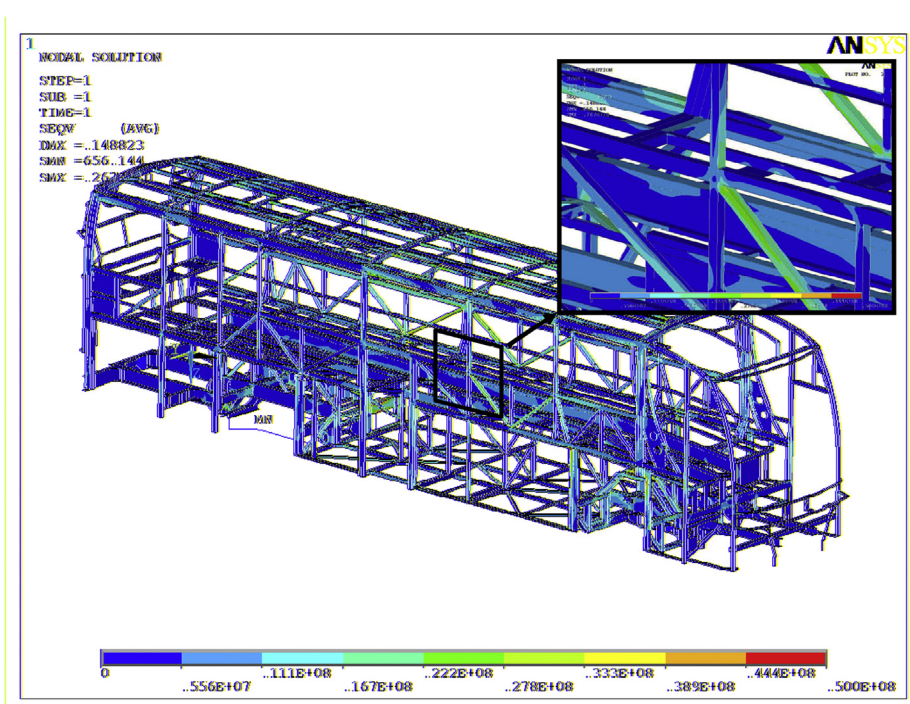

Fig. 2. Stress distribution, in Pa, due to a torsional loading case.

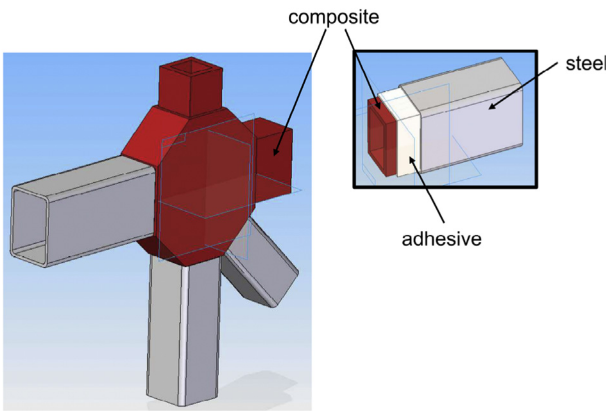

Fig. 4. Proposed new design of CFRP node adhesively bonded to steel beams of the bus structure.

$$\tau = \frac{F}{A} \quad (1)$$

where F is the axial force acting in each beam and A is the adhesive overlap area.

Adhesives work efficiently facing traction-compression or pure shear stresses, nevertheless, peel stresses caused by torques are the most harmful stress for any adhesive bonding. The design of our bond minimizes peel stresses to practically negligible values. Degrees of freedom between beams and composite part have been decreased, avoiding the relative movement between both elements by confined adhesive design [25]. The majority stresses of the bonding perform over the steel beam and the composite part.

The reference node is formed by 5 beams, thus 5 Steel-Adhesive-CFRP contact zones appear. To ensure that the bending will be avoided by geometrical interference of the beams meeting in the node and taking into account their averaged dimensions, an adhesive overlap of 50 mm is used.

From the developments exposed in the experimental procedure, the value of the stresses that the adhesive bonding should resist are calculated. Shear stress components are distributed along the coordinate axes as is shown in Fig. 3.

Table 3 shows the shear stress values obtained for each studied beam. These values have been calculated taking into account the most demanding service conditions for the adhesive joint. Under these conditions the adhesive joint of each beam will be responsible for resisting the resulting force F in its axial direction. Real confined adhesive design allows obtaining lower stress request, as it is explained above. From the most unfavorable case, we can get an idea of the safety margin in the obtained solution for the raised problem.

In terms of the adhesive selection, it is important to remark that this project allows for reducing the effects of fatigue caused by welded joints. Thus, it will be necessary to diminish the rigidity of the structure. This factor is essential in order to choose the adhesive. The selected adhesive must be sufficiently elastic-plastic, so that the stresses of fatigue in the structure of the bus are attenuated. In this paper the main objective is to study the viability of

Table 3
Shear stress values due to the torsional loading case.

Beam	F [N]	A [mm^2]	τ [MPa]
6	518.5	8400	0.06
11	2361.2	10800	0.22
37	4323.7	10800	0.40
39	1999.5	8400	0.24
44	3564.4	8400	0.42

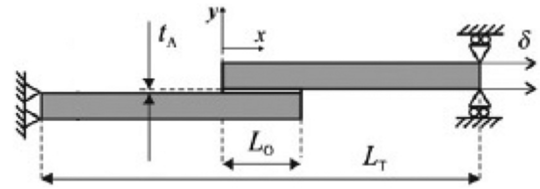

Fig. 5. Geometry and dimensions of studied Single Lap Joint specimens [28].

using a polyurethane based adhesive for the multi-material joint in the new concept of node. Previous works [26] reveal that for ductile adhesives like polyurethanes, 2 mm thickness leads to a better compromise between fracture toughness against traction and shear loads. The same adhesive thickness of 2 mm is used in single lap joints specimens and in the final node design to reproduce as accurately as possible the work conditions of the node.

4. Experimental tests to characterize the adhesive for the multi-material joint

4.1. Specimens

SikaTack Drive®, provided by SIKA SAU SPAIN, is selected as adhesive. It is a very elastic-plastic structural adhesive. Currently, this adhesive is used for bonding windshields of cars. As it is a structural adhesive, it has enough capacity to support the stresses that the node will be subjected to, providing the structure with the necessary elasticity to absorb fatigue stresses. On the other hand, as

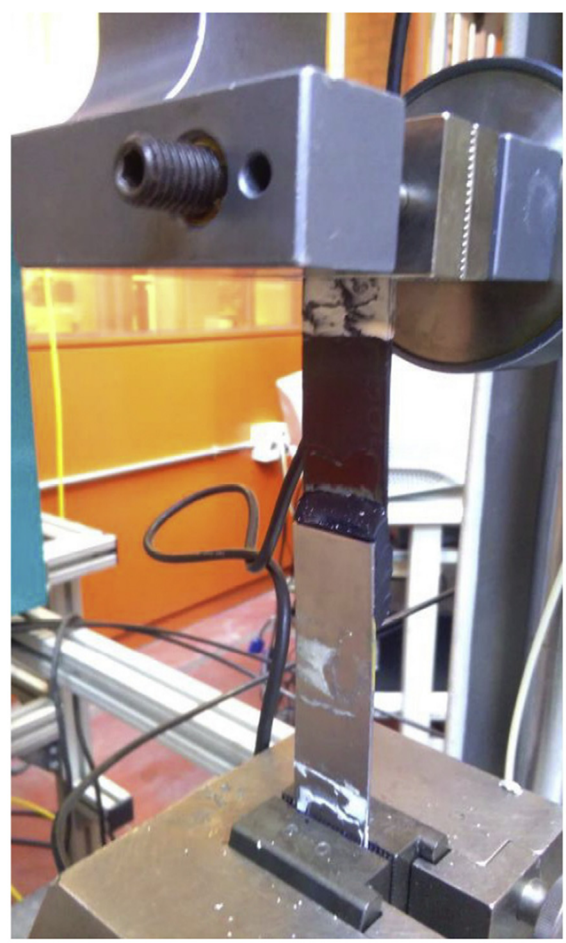

Fig. 6. Shear tests on specimens.

Table 4
Obtained values of shear tests for 5 tested single lap joint specimens.

	τ_{max} [MPa]	$\delta_{\tau max}$ [%]	$\gamma_{\tau max}$ [%]	Stiffness [MPa]	Type of break
Specimen 1	4.3	33	76	13.0	Cohesive
Specimen 2	4.1	33	76	12.5	Cohesive
Specimen 3	4.1	35	73	11.6	Cohesive
Specimen 4	4.8	38	76	12.5	Cohesive
Specimen 5	4.6	38	76	12.0	Cohesive
Average	4.4±0.3	35±2	75±1	12.3±0.5	

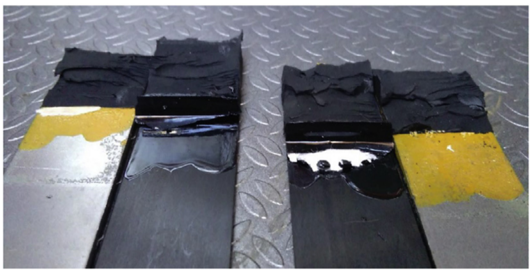

Fig. 7. Cohesive break.

it is polyurethane based adhesive, it has adequate behaviour against external agents, such as humidity and temperature. So it is suitable for the raised problem.

The new design of the joint was made in order to achieve the most favorable conditions for the adhesive bonds, minimizing peel stress and obtaining mainly shear stress.

For this study, five adhesive joint specimens of composite material and steel were manufactured. The composite used in the tests is Sika Carbodur ®, provided by SIKA SAU SPAIN. The other adherent is structural steel which is widely used in bus body structure manufacturing. Measurements for steel specimens are: length $L_S = 100$ mm, width $W_S = 25$ mm and thickness $T_S = 1.6$ mm. CFRP specimens have been manufactured through a pultrusion process. Specimens are cut with the following measurements: length $L_{CFRP} = 100$ mm, width $W_{CFRP} = 25$ mm and thickness $T_{CFRP} = 1.2$ mm.

Single Lap Joint specimens have been developed for carrying out shear tests. Geometry and characteristic dimensions of Single Lap Joint specimens are shown in Fig. 5. The following measures are used: adhesive thickness $t_A = 2$ mm, total specimen length $L_T = 175$ mm and adhesive overlap $L_0 = 25$ mm. Although EN 1465:2009 standard [27] establishes an adhesive overlap of 12.5 mm, previous works reveal that 25 mm overlap length is more appropriate for ductile adhesives [26].

4.2. Surface treatments

It is necessary to ensure a cohesive breaking (inside the adhesive) of the joint working with adhesives, being adhesive breaking (in the substrate-adhesive interfaces) undesirable. Therefore, the right surface treatments on the bonded substrates must be developed. For this work, different tests have been carried out, with the objective of determining the best possible surface treatment for the raised joint.

For steel substrate, the surface treatment consists in a 3 steps process. Step 1, is a sanding process with P180 sandpaper. Step 2, is a cleaning process with Ethanol solvent. And Step 3 consists of the application of a thin layer of a primer, Sika Primer 204 N®. Primers are products that favor the bond forming chemical bonds between the interfaces substrate-adhesive. Another benefit of primers is that it allows to protect the joint against corrosion problems.

For CFRP substrate, firstly, a cleaning process with Ethanol solvent is carried out. Then, an atmospheric pressure plasma treatment (APPT) is done. In the APPT process, an ionized gas is applied on the surface of the material through a torch. This treatment can be used for both polymers and metals, introducing polar groups on the surface of the material, increasing the surface energy value, making possible a better bond with the adhesive or with the primer [29]. The treatment has been used to activate the surface of the polymer (CFRP), with 3 m per minute of torch speed and 6 mm of torch-specimen distance. Finally, a thin layer of primer (Sika Primer 215 ®) is applied on the activated CFRP surface.

4.3. Shear tests

The shear tests were carried out, according to EN 1465:2009 standard [27]. These tests allow to accurately evaluate the suitability of the adhesive and surface treatment used for the considered problem. Shear tests are carried out in a Microtest ® universal testing machine, see Fig. 6, with 2 mm/min of test speed.

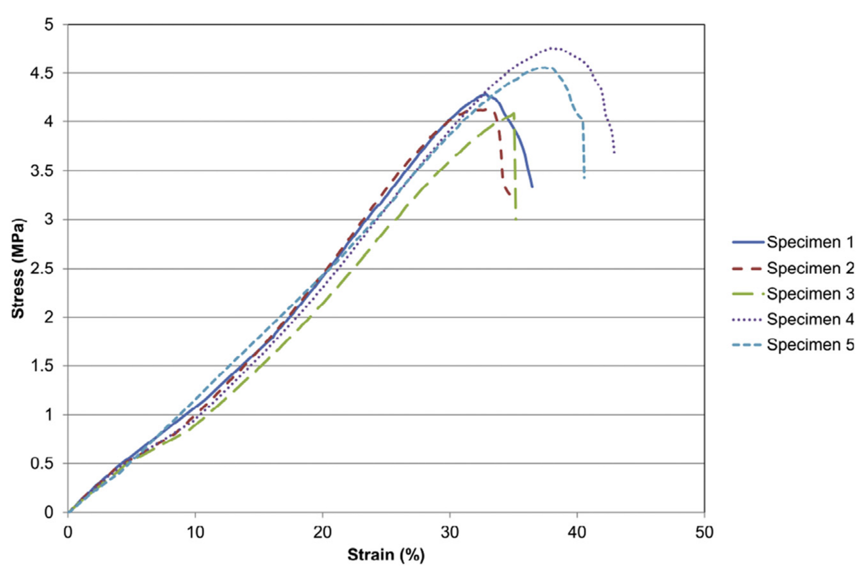

Fig. 8. Stress-Strain curves of the studied single lap joint specimens.

5. Results and discussion

Table 4 shows maximum stress (τ_{max}), normal strain for maximum stress ($\delta_{\tau max}$), shear strain for maximum stress ($\gamma_{\tau max}$) and stiffness values for each specimen. Likewise the type of break is shown too. Fig. 7 shows a cohesive break for one of the specimens used in the shear tests.

Stress-Strain curves of Fig. 8 show the comparison in terms of behaviour of the five studied specimens. The slope of the curve is directly related to the stiffness of the joint, and due to the cohesive failure, dispersion is minimal among the different specimens. This low dispersion can also be appreciated in Table 4 in the Stiffness column.

The selected adhesive shows deformation values higher than 30% for maximum shear stress. This is interesting for the raised problem, so that the rigidity of this part of the structure will be decreased compared to adjacent nodes, and consequently stress will be redistributed towards the surroundings and fatigue problems will also be reduced in the critical area. Maximum shear stress values are also enough, just like the resulting stresses as has been previously shown in Table 3.

6. Conclusions

The present study has analyzed the viability of using a polyurethane based adhesive to connect a new proposed concept of joint made with CFRP to the steel bus structure. From the performed lab test it was possible to conclude that:

- The raised adhesive joint shows values far superior to the stresses that it must bear, an order of magnitude higher than the most unfavorable service condition posed.
- The new raised adhesive joint allows to obtain greater elasticity at the reference node, decreasing the relative rigidity of the surroundings and minimizing mechanical fatigue.
- By replacing welded joints by new CFRP components, it is possible to decrease the weight of the structure, allowing greater efficiency by reducing fuel consumption.

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